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Crab Cavities for the LHC Luminosity Upgrade

Project Document, version 20-Aug-10

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CRAB CAVITIES FOR THE LHC LUMINOSITY UPGRADE

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1 INTRODUCTION

The LHC is now successfully operating for physics and progressing towards its design goals. It is the energy frontier machine in high energy particle physics for the foreseeable future. Maximum effort is now being put into to ensuring that that machine and experiments operate optimally at their design performance in order to allow full exploitation of the physics potential of the LHC. However, already in 2006, a subsequent major luminosity upgrade (SLHC) was presented [1]. This focused on the need to achieve increased beam intensity and reduced beam sizes at interaction points (IPs) for higher luminosities. Increased beam intensities were to be achieved by upgrades of the injector chain and the reduction of the beam sizes by an upgrade of the inner triplets at the experimental interactions regions (IRs) 1 and 5 of LHC. This upgrade was primarily needed as the existing triplets would have reached the end of their lifetime if LHC would operate at design parameters from 2007. The use of transverse deflecting cavities, known as crab cavities, was also proposed to correct the geometric effects of the wider crossing angles as a consequence of the reduced beam sizes with the IR upgrade. A number of collaborations have been put in place to study the performance of crab cavity schemes and to produce designs for such cavities. Excellent progress has already been made.

Due to the delayed start-up of LHC for physics, as well as revised time scale and cost of a full injector upgrade, the focus on luminosity increase is now on making a set of improvements to the existing injectors, still making an important gain on the maximum intensity [2], and on a High Luminosity LHC (HL-LHC) [3]. The latter is again based on upgrade of inner triplet quadrupoles, but on more powerful magnets with larger apertures using Nb_3Sn technology. It now becomes all the more essential to correct the effects of the IR crossing angle and also to provide a means of *"luminosity levelling"* during the coast. Crab cavities are the best candidate for achieving both of these. The study on crab schemes and on crab cavities is therefore a major ingredient of the HL-LHC upgrade project [4]. The upgrade is planned to take place in 2020-2021. A design study is now in preparation for the HL-LHC. A Preliminary Design Report (PDR) will be produced by the end of 2013, to be presented to the CERN Council. A Technical Design Report (TDR) will follow early in 2015.

The present document briefly describes the planned LHC luminosity upgrade, the role of crab cavities and their design options and reviews the present status of work on crab cavities. It outlines a strategy towards the realization of a full crab cavity system in LHC as part of HL-LHC. It describes how crab cavity study and prototyping work should proceed to the point of the TDR and gives a description of the work plan which would follow in subsequently to produce pre-series modules followed by the construction of the full crab cavity system.

2 LHC LUMINOSITY UPGRADE PLANS

2.1 GENERAL IR UPGRADE PLAN

Operating at the beam-beam limit, the luminosity upgrade of the LHC is foreseen to follow two main paths. The first is a reduction of β^* at the collision points using upgraded inner triplet quadrupoles with a simultaneous compensation of the Piwinski angle via crab crossing [5]. The second path is to obtain significant increase in bunch intensities beyond the nominal intensities (factor 1.5-5) [6] or/and a reduction of beam emittances (factor 2 or smaller). Although significant challenges confront both paths, the final upgrade is likely to exploit a combination of the two paths. The present strategy is based on the full exploitation of the present LHC until 2019, with a single IR upgrade, using Nb_3Sn, taking place in 2020/2021 and coinciding with major upgrade of the experiments. The preliminary schedule of LHC operation, shutdown periods and planned upgrades is shown in Figure 1.

Figure 1: Preliminary LHC schedule for the period 2010 – 2021.

2.2 GOAL OF THE CRAB CAVITY PROJECT

To fully exploit the inner triplet upgrade, crab cavities are essential. They are the instrument of choice both for compensation of the crossing angle and for luminosity levelling, allowing for optimum integrated luminosity during the coast without the need of excessive peak intensities. The final goal of the crab cavity project described in this document is to obtain a significant luminosity increase by installing local crab cavities in IR5 and IR1. This installation will be a part of the revised luminosity upgrade described above, following the planning of Figure 1, i.e. by mid 2021. It will require four compact cavities for each high luminosity IR, two per beam on either side of IP. All cavity and associated equipment have to be fully commissioned and ready for beam with ultimate intensities in mid-2021. To mitigate the risk of the not yet established technology of the compact crab cavities, which would be required for this final goal, more conventional elliptical crab cavities are another important element of the project. The overall schedule of the crab cavity project, synchronized with the expected LHC operation schedule and the HL-LHC project proposal is shown in Figure 2.

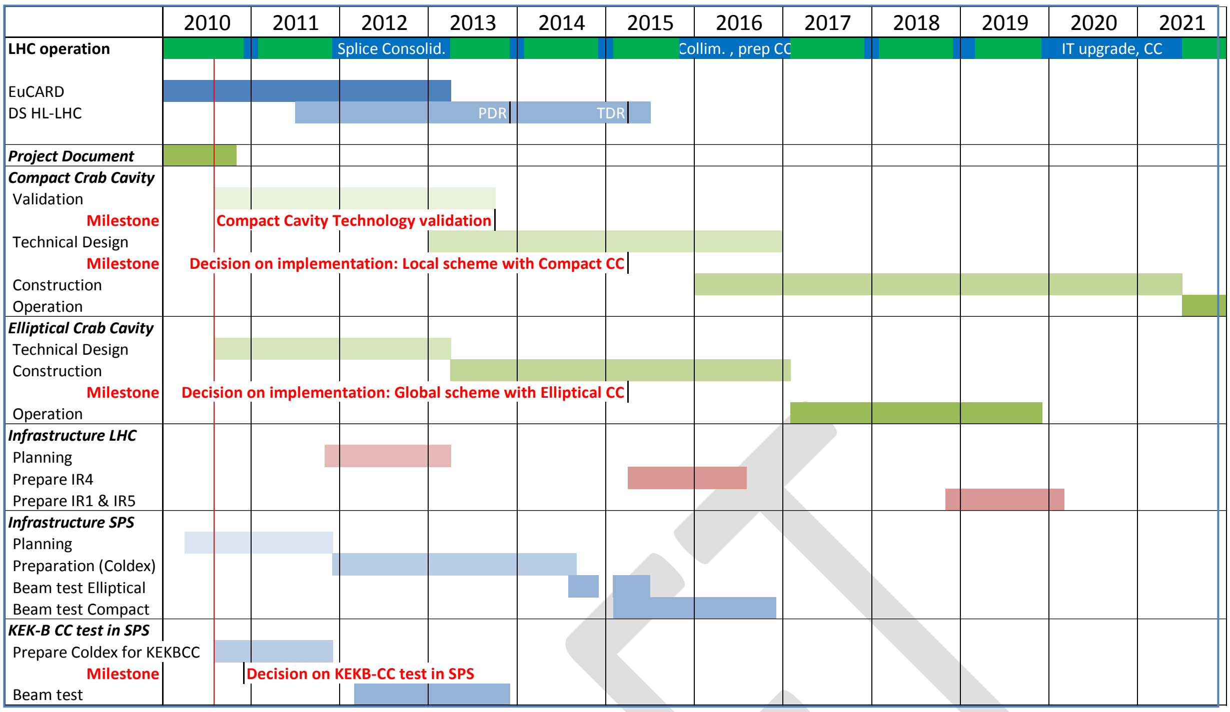


Figure 2: Overall schedule of the crab cavity project synchronized with the expected LHC operation schedule and the HL-LHC project proposal.

2.3 Assumed Beam Parameters

Table 1: Beam parameters for the LHC nominal and upgrade lattices.

Parameter	*Unit*	*nominal*	*upgrade*
Energy	[TeV]	7	
Protons/Bunch	[10^{11}]	1.15	1.7
Bunch Spacing	[ns]	50…25	
$\varepsilon_n\,(x,y)$	[μm]	3.75	3.75
σ_z (rms)	[cm]	7.55	
Bunch Length ($4\,\sigma$)	[ns]	1.0	
Longitudinal Emittance	[eVs]	2.5	
β^* at IP1, IP5	[m]	0.55	0.25…0.14
Betatron Tunes		{64.31, 59.32}	
Piwinski parameter: $\frac{\theta_c\,\sigma_z}{2\,\sigma^*} = \frac{\Delta_{in}\,\sigma_z}{2\,\beta^*}$		0.65	1.4…2.5
BB Parameter, ξ, per IP		0.003	0.005…0.008
Crossing-angle: θ_c	[μrad]	285	315…509
Main RF	[MHz]	400	
Crab RF	[MHz]		400
Peak luminosity w/o crab cavity	10^{34} cm^{-2}s^{-1}	1	3.3…3.8
Peak luminosity with crab cavity	10^{34} cm^{-2}s^{-1}	1.2	5.8…10.3
Pile up events per crossing		19	44…280

Some relevant beam parameters for the LHC nominal and upgrade lattices are given in Table 1. Significant luminosity increase can be expected by crab cavities for small β^*; this is also depicted in Figure 3. It is also evident that the number of events per bunch crossing is leading to a substantial pile-up for small β^*; this can be reduced to manageable size by the use of *"luminosity levelling"*. There are many possible deviations from these parameters possible and scenarios proposed, but the parameters given in Table 1 will be used in this document as reference.

3 CRAB CAVITIES AND CROSSING ANGLE

The reduction of β^* below nominal is attractive and technically feasible, but the presence of the parasitic interactions requires a proportional increase of the crossing angle. Therefore, the full potential of a β^* reduction can only be realized by recovering the geometric loss of the crossing angle either via a crab compensation scheme or an early separation scheme [7]. The potential luminosity gain with crab cavities as function of β^* is shown in Figure 3. Similarly, the crossing angle can also be increased with crab cavities to remain at the beam-beam limit with increased bunch intensity and therefore provide a larger integrated luminosity. In addition, the crab cavities offer a natural luminosity levelling knob to maximize the integrated luminosity and to optimize the lifetime of the IR magnets in terms of radiation damage [6].

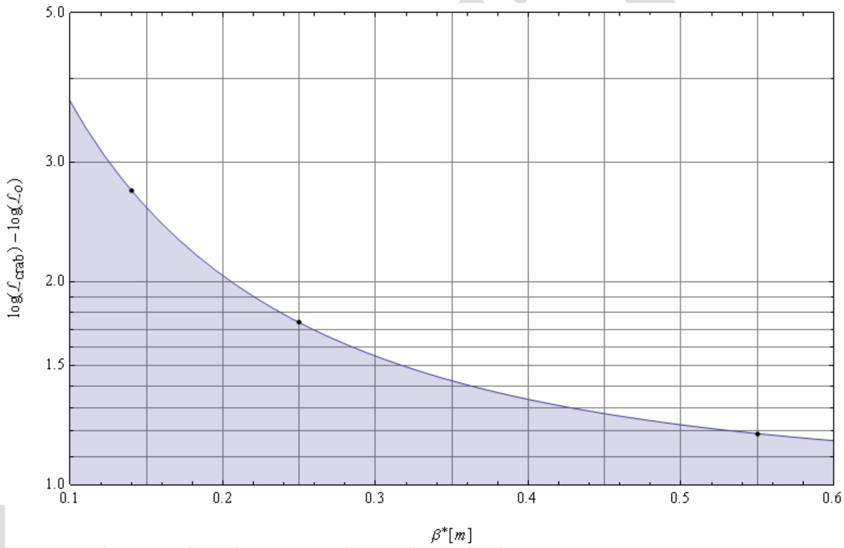


Figure 3: Possible peak luminosity gain by crab cavities as a function of β^*. The effect of the constant separation for parasitic interactions is taken into account. The points mark the values of β^* mentioned in Table 1.

3.1 GLOBAL AND LOCAL SCHEMES

Two schemes have been considered for crab crossing in the LHC. Only the high luminosity regions (IP1, IP5) are considered. The nominal and most flexible option without severe optical constraints is realized with a fully local crab crossing scheme at each IP. This requires one crab cavity per beam on either side of each IP, i.e. 4 cavities per IP, 8 cavities in total for IP1 and IP5. An alternate global scheme with a minimum of one cavity per beam placed in the IR4 dogleg region is also a viable option. This option was considered for a prototype tests in the original Phase 1 proposal and is included in HL-LHC, but not as the baseline concept. It was seen as an important step in validating the crab cavity concept in the LHC with hadrons before the implementation of a complete local scheme, and its study remains necessary now for risk mitigation and possibly for a limited luminosity increase in the LHC before the local scheme can be fully implemented.

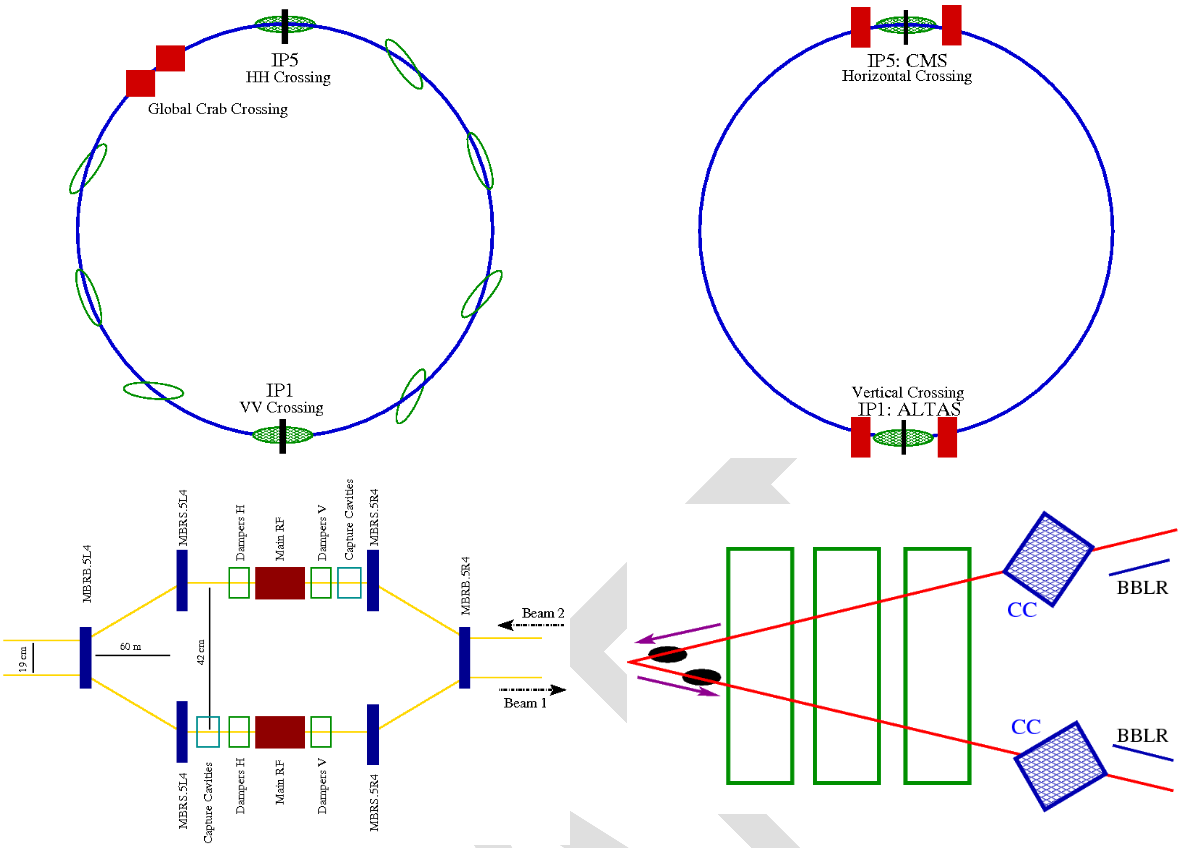


Figure 4: Schematic for a Global scheme (left) at IR4 and Local scheme (right) at IP1 and IP5.

3.2 Technology Choice and Spatial Constraints

In order to sustain the surface fields at the required gradient, superconducting technology is essential; space restrictions, voltage requirements and impedance considerations strongly rule out a normal conducting option. Two types of cavities are under study. "Conventional" elliptical cavities as already used at KEK. The design and construction of such cavities are technically viable; however the physical size for frequencies under consideration (400…800 MHz) pose a significant integration problem for their use in a local scheme [8]. They could however be used for the global system at IR4 at 800 MHz due to the existing dog-leg (see Figure 4). IR4 has the distinct advantage of larger beam-to-beam separation. It is also the region where all present day LHC RF systems are installed. However, this scheme poses severe constraints on the betatron phase advances between IP1, IP5 and the crab cavities, as well as on the crossing scheme at the two IPs. Presently the beam cross in the vertical plane at IP1, in the horizontal plane at IP5; a single crab cavity polarization could thus increase luminosity only in one IP.

Use of conventional cavities for local schemes around IRs 1 and 5 would require the creation of 2 dog-leg sections per IR with 8 very strong dipole magnets (7 T). Substantial civil engineering work would be needed to make the required space along with the associated cryogenic infrastructure. This led to the concept of "Compact" cavities. These cavities have unconventional geometries not yet implemented in superconducting technology. However, they promise to fit within the LHC constraints (see Figure 5) in the existing tunnel and reveal more favourable surface fields' characteristics than the conventional cavities. Progress on compact cavities is very encouraging; there are at least four potential designs under study. The strategy now adopted for the crab cavity program, following the Crab Cavity workshop (LHC-CC09) at CERN, and aligned with the new LHC IR upgrade strategy, is to target compact cavity development. Nevertheless the conventional design at 800 MHz developed within the US-LARP collaboration is retained as a back-up solution if needed. This is in view of the technological challenges and risk that do remain with the compact cavity solution.

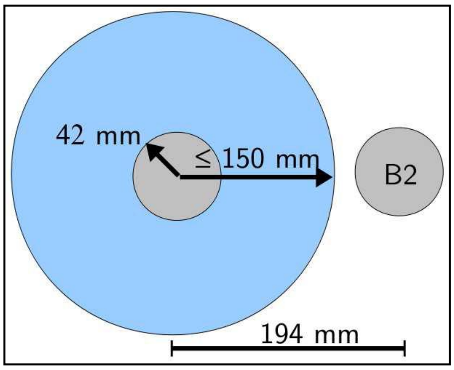


Figure 5: LHC beam separation and aperture constraints.

Table 2: Aperture constraints for the local scheme at IR1 and IR5; constraints for the global scheme in IR4 region consisting of the dog-leg.

	Element IP1/IP5	Aperture – H [mm]	Beam-to-beam separation [mm]	Max outer radius [mm]	*L* [m]
Local	D1	134			10
	Crabs	84	194	150	10
	D2	69			10
Global	D3	69	420	395	9.45
	Crabs	84	220 (300)	195 (275)	10
	D4	73	194	169	15.5

3.3 Conventional Elliptical Cavities

A two-cell elliptical cavity at 800 MHz was developed as a baseline deflecting structure. The nominal voltage for the two-cell cavity was set at 2.5 MV for which the surface electric and magnetic fields are 25 MV/m and 83 mT respectively. These surface fields are well below the state-of-the-art SRF cavities considered for the ILC and therefore allow for sufficient operational margin. Due to tight tolerances on narrow band impedances, the cavity modes need to be strongly damped. Therefore, special coupler designs targeted at specific modes were developed (see Figure 6) [10]. Alternative damping designs were also developed for the two-cell design to meet the damping specifications [11, 12]. A conceptual design of the cryostat was also developed for the two-cell baseline cavity-coupler to satisfy the IR4 beam line configuration (see Figure 5). A modular structure was adopted for additional cavities if needed. The helium box contains interconnection ports for the second cavity. A service port is suggested for the He inlet/outlet ports as well as for the RF couplers (Main coupler as well as Same, Lower and Higher Order Mode (SOM, LOM and HOM) couplers. The outer diameter is constrained by the limited space between Helium vessel and cryogenic line. A design of the main power coupler which is nominally oriented in the horizontal plane requires a vertical output due to beam line configuration. The horizontal length of the coupler is limited to ~150 mm. A possible solution is a T-connection similar to the KEK Tristan-type ERL coupler [13].

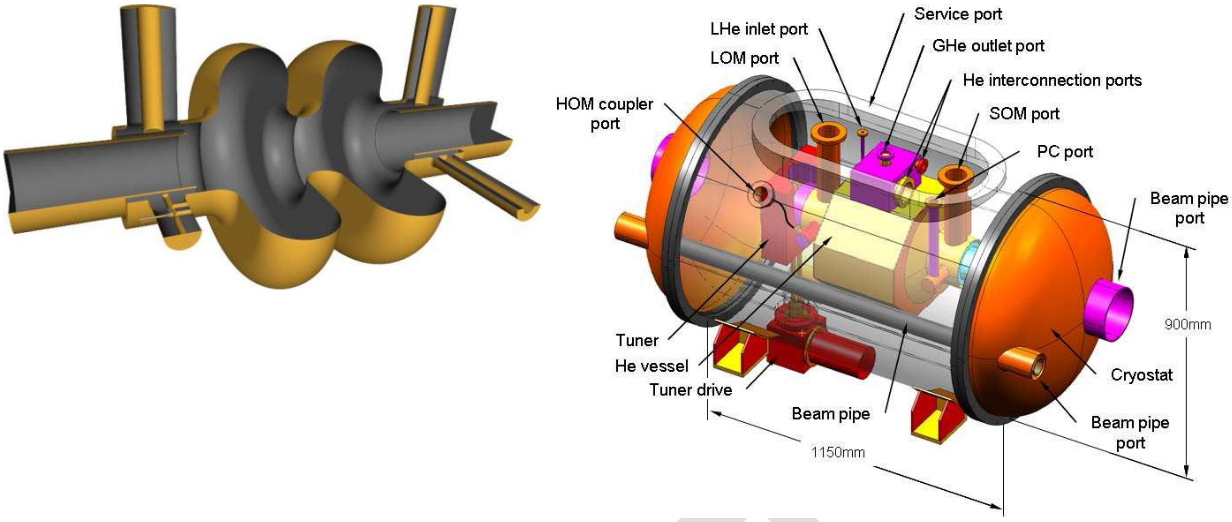


Figure 6: Schematic of the two cell elliptical LHC crab cavity [10] and cryostat [2].

3.4 Compact Cavities

A crab scheme local to the collision point offers the most flexibility in optics and crossing scheme. Due to the tight aperture constraints near the IP (see Table 2), deflecting structures with a compact footprint are essential. The effort to compress the cavity footprint has resulted in several new deflecting mode geometries. Apart from being significantly smaller than their elliptical counterparts, for some of these new geometries the deflecting mode is also the fundamental mode. This paved the way to a new class of cavities at lower frequencies (400 MHz) which is also preferable from RF linearity considerations [14].

The ratio of the kick gradient to the peak surface fields for some designs is lower by a factor of 2 or more than the elliptical counterpart. Therefore, theoretically, a kick voltage larger by a factor of 2 may be expected, assuming the surface field limitations are similar to elliptical cavities. Four possible designs are shown in Figure 7. These cavities also have the added advantage of large separation in frequency between the deflecting mode and other higher order modes. Therefore, HOM damping becomes simpler. Nevertheless, the coupler concepts developed for the elliptical design are being adapted to achieve a similar level of damping in the compact cavities. Prototyping of some compact designs is getting underway.

a) b) c) d)

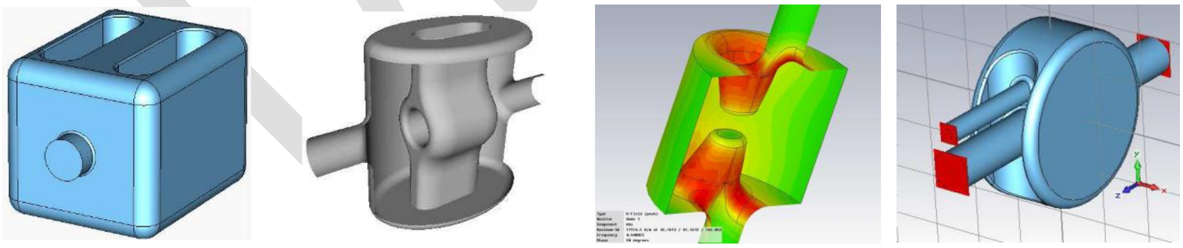


Figure 7: Compact cavity designs: a): Half wave double rod cavity [23] b): Half wave single rod cavity [24] c): Double rod loaded cavity [20], d): Rotated pill-box Kota cavity [25].

3.5 Finalizing Cavity Specifications

Getting towards performance specs needed for each compact cavity design, based on a common parameter set, e.g.

- Beam separation 194 mm CL to CL
- Beam pipe diameter 42 mm

- Frequency 400 MHz
- Identical integrated kick

4 CURRENT STATUS

4.1 EXISTING COLLABORATIONS

Crab cavities were initially proposed in the framework of the CARE-HHH and US-LARP programs in 2005 as a potential scheme to benefit the luminosity upgrade program. Since then the activity has been supported to perform feasibility studies at the level of design layout and RF structures. A voluntary collaboration was put in place with the initiation workshop, LHC-CC08, which was held at Brookhaven National Lab.

As a consequence, a yearly workshop series has commenced to discuss the progress and challenges of the LHC crab cavity proposal. A monthly web meeting to discuss the technical progress of the crab cavities is in place with participation from the EuCARD in Europe, US-LARP in the U.S. and KEK in Japan. Additional participation to fabricate the technology is also active from small businesses in the US via small business funding (SBIR/STTR program) from the US Department of Energy (DoE). A comprehensive database of the general progress on this subject including links to workshops and meeting can be found at [26]. A potential new collaboration with French Laboratories, Universities and Industry is in preparation.

4.1.1 EUCARD WP10.3, "LHC CRAB CAVITIES"

EuCARD is a common venture of 37 European Accelerator Laboratories, Institutes, Universities and Industrial Partners involved in accelerator sciences and technologies. The project is an Integrating Activity co-funded by the European Commission under the Seventh Framework Programme (FP7) and runs from April 2009 to March 2013. Its main goal is to upgrade the large European research accelerators by R&D on innovative concepts and techniques, thereby offering researchers the best facilities.

For the EuCARD work package 10.3 [27], CERN, STFC and the Cockcroft Institute with the Universities of Lancaster and Manchester collaborate on the following relevant main subjects:

- determine the full LHC system requirements for the crab cavity system,
- develop a suitable crab cavity design which meets these requirements,
- develop suitable input and mode couplers to allow for damping of the dangerous trapped modes,
- develop a suitable frequency tuner,
- fabricate a model test cavity for validation of expected cavity performance,
- perform mode characterization measurements,
- develop suitable LLRF systems that can control the amplitude and phase of the crab cavities,
- perform low power phase and amplitude qualification measurements.

The first of the above subjects is now accomplished; specifications for beam requirements, impedance constraints, operating conditions, RF noise, lattice layout, integration and most importantly machine protection were written [28]. The specifications of the RF structure and its ancillaries will follow the system requirements and the choice of technology.

RF experts from Cockcroft institute at the University of Lancaster, together with colleagues from Jefferson Lab and the STFC, have also been involved in the development of the waveguide damped, two-cell elliptical cavity and of a four-rod compact deflecting cavity [29]. The research is focused on the optimum cavity design and damping schemes for both structures along with studies on multipacting, thermal and mechanical issues. A normal-conducting model test cavity is foreseen inside the EuCARD program; a superconducting cavity prototype which would validate the RF design could be fabricated as soon as funding becomes available.

4.1.2 US PARTICIPATION/CONTRIBUTIONS

Within the framework of the US-LARP program, scientists from the associated US laboratories (BNL, FNAL, JLAB, LBL and SLAC) have significantly contributed towards the proposal and feasibility studies since 2005. This task is funded at the level of $320 k per year for 2008-09 and is anticipated to increase for the following years. US-LARP has taken a lead role in coordinating the feasibility study in close collaboration with CERN. Contributions towards the feasibility study range from machine layout, potential schemes, collimation studies, operational scenarios, RF noise with beam-beam, machine protection and other issues. The primary technical contributions include baseline two-cell elliptical cavities and single-rod and double-rod half wave resonators as potential candidates for the compact cavities.

Contributions also from small business innovative proposals in close collaboration with the US-LARP institutions have been active since 2008. Two companies, AES and Niowave, have each been awarded and successfully completed the Phase I part of the SBIR/STTR program. This phase includes a transition from the RF design to a complete mechanical and thermal model leading towards details on fabrication process. Upon approval of Phase II, these companies commence the final technical design and fabrication of the compact cavities proposed within the US-LARP collaboration.

4.1.3 FRENCH PARTICIPATION/CONTRIBUTIONS

Within the scope of a new proposal called "Grand Emprunt" launched by the French Government, the CEA, the CNRS/IN2P3 laboratory LAPP Annecy and the LPSC in Grenoble have declared their interest in close collaboration with CERN to embark on the development of the baseline two-cell elliptical cavity and ancillary components required for a validation of the RF design and HOM damping. A cryomodule to host the two-cell cavity and coupler structure may be within the scope of this proposal which could then be used for beams tests in the SPS and the LHC. Since this collaboration is not yet fully established, it will be described in more detail in 9.4 below.

4.1.4 JAPANESE PARTICIPATION/CONTRIBUTIONS

KEK

As pioneers of implementing a crab scheme in the e^+/e^- collider, KEK-B, the participation and contributions from KEK-B towards LHC crab cavities is vital. An initial study the feasibility of KEK-B cavities in the SPS have resulted in a positive outcome [14]. A detailed plan and cost estimate is underway to take a decision by end of 2010 for the use of KEK-B cavities in the SPS. Design studies on both conventional and compact studies are taking place but a plan for construction of a cryomodule is still not foreseen.

4.2 REVIEW OF RESULTS ACHIEVED AND REMAINING STUDY ISSUES

4.2.1 MACHINE PROTECTION

Due to the immense stored energy in the LHC beams at 7 TeV (350 MJ), protection of the accelerator and related components is critical. For example, at nominal intensity and 7 TeV, 5% of a single bunch is beyond the damage threshold of the superconducting magnets [15]. Approximately, 200 interlocks with varying time constants ensure a safe transport of the beam from the SPS to the LHC and maintain safe circulating beams in the LHC. A worst case scenario for detecting an abnormal beam condition is 40 μs (½ a turn), and the corresponding response time to safely extract the beams is about 3 turns (see Figure 8).

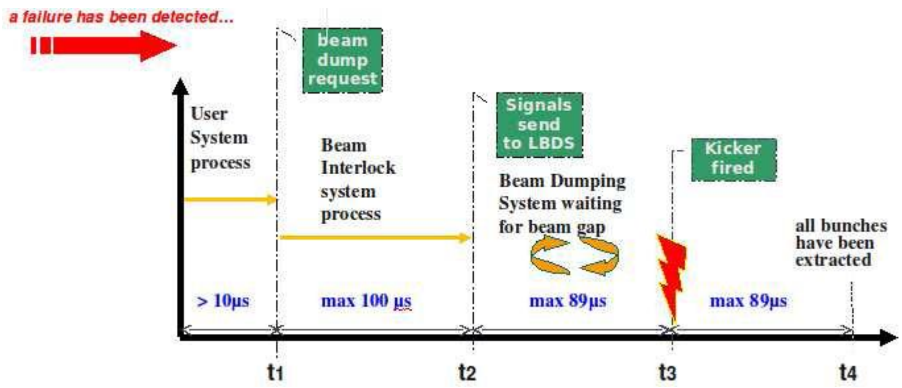


Figure 8: Sequence of failure detection and safe extraction of the beam.

Crab cavity failures can abruptly change particle trajectories and induce unwanted beam losses. Single turn failures caused due to sudden cavity quench, power amplifier trips, abrupt RF phase changes and other potential causes. Slow failures caused by vacuum degradation, IR cavity to cavity voltage and phase drifts and others. Any crab cavity related failure must fall under the shadow of the 3-turn extraction time. The high Q_{ext} could favour a slow voltage ramp down, but the voltage slope can be strongly driven by the beam. Therefore, active feedback is essential to guarantee machine protection.

4.2.2 Optics & Layout

The nominal LHC optics has small beta-functions (see Figure 9) in IR4 and therefore requires substantial cavity voltage. We propose an anti-squeeze in the crab cavity section of IR4 to reach the maximum beta-functions for the prototype tests without altering the phase advance. The phase advances for beam 1 and beam 2 are (7.636, 8.185), which are close to the optimum phase advances for the IR4 location which are (0.655, 0.155) respectively. The apertures for the anti-squeezed optics are within specification and require four quadrupoles to be powered by new bipolar power supplies. Detailed studies on the actual anti-squeeze sequence are underway to have a smooth path between injection and collision optics. Studies to compute dynamic aperture and effects of chromatic aberrations are underway [16]. Figure 9 also shows the tunability limits of the phase advance as constrained by the aperture limits. A wide range for tunability is available which enables an additional knob for voltage optimization.

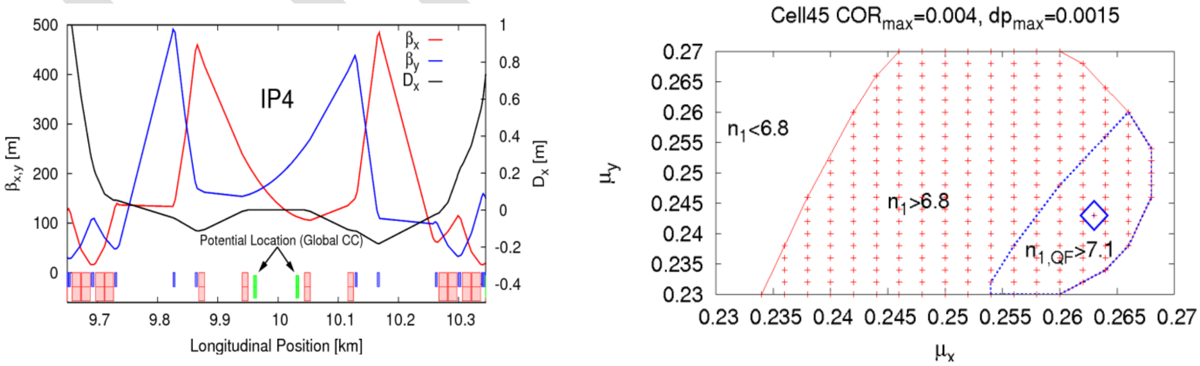


Figure 9: Nominal optics and magnetic elements in the IR4 region of the LHC (left). Potential locations for crab cavities are plotted in green. Tuning range of the LHC phase advance per arc cell (right).

For the local scheme, a layout and preliminary optics to accommodate conventional cavities in the IR1 and IR5 region were developed. An approach using additional D11 & D22 dipoles to separate the two beam lines to ~25 cm (see Figure 10). These additional dipoles would operate at 7 T and 4 T respectively and the distance between the presented D1 and D2 magnets is increased by about 20 m to ease the insertion of these new dipoles. The immense amount of hardware and services required to create these dog-legs in the IRs is impractical; therefore compact cavities compatible with the existing footprint are required.

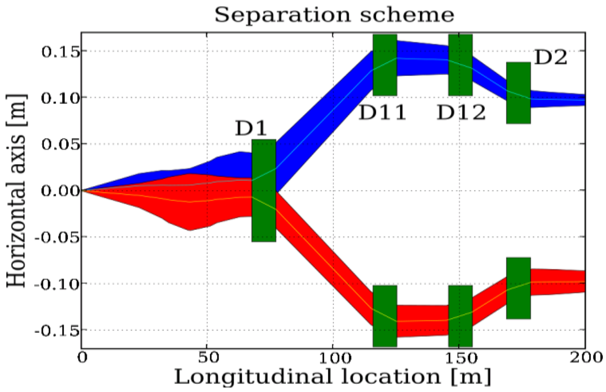


Figure 10: Layout of a dogleg to accommodate conventional cavities in the IRs 1 and 5 using additional dipole to separate the beams by 25 cm transversely. The 10 σ envelope of the two beams is plotted.

4.2.3 Impedance

The LHC impedance is dominated by the numerous collimators [17], but additional impedance (both narrow band and broadband) from sources like crab cavities need to be minimized. It is estimated that single and coupled-bunch longitudinal modes above 2 GHz will be Landau-damped due to the frequency spread of synchrotron oscillations. Tolerances can be set by estimating the impedance requirements from [18]. For nominal intensities, the longitudinal impedance should be limited to less than 60 kΩ at 450 GeV and 10 kΩ for ultimate intensities of 1.7×10^{11} protons/bunch [19]. In the transverse plane the natural frequency spread, chromaticity, bunch-by-bunch transverse damper and Landau octupoles should also damp potentially unstable modes above 2 GHz. The stability limit from Landau octupoles at 7 TeV can be formulated in terms of a maximum limit on tune shifts ($\mathrm{Re}\{\Delta Q\} < 3 \times 10^{-4}$, $\mathrm{Im}\{\Delta Q\} < 1.5 \times 10^{-4}$). Assuming that the sampling frequency falls on the HOM resonance, damping to Q_{ext} of 100…1000 is required to stay within 2.5 MΩ/m derived from the damping time of 60 ms at 450 GeV. An additional factor of the local beta-function normalized to the average beta-function should be taken into account.

4.2.4 RF Noise and Stability

RF phase noise in crab cavities leads to dynamic offsets at the collision point given by

$$\Delta x_{IP} = \frac{c\theta}{\omega_{RF}} \delta\phi$$

In the presence of beam-beam and random dipole kicks, the dynamic offsets can lead to emittance growth with higher frequency noise being more dangerous [12]. Measurements at KEK-B show the side bands of the RF spectrum due to modulated phase noise at frequencies from 50 Hz to 32 kHz.

Figure 11: Spectrum of the KEK-B crab cavities during operation with a frequency span of 200 Hz (left) and 200 kHz (right). The main 509 MHz line is modulated by sidebands at −60 dBc to −80 dBc (courtesy KEK-RF group).

Noise studies were carried which consisted of scanning the frequency and amplitude of the RF phase noise in the CCs and measure the corresponding beam size blow-up. The first visible effects occur at about −60 dBc for both rings without beam-beam. This corresponds to about 0.1° RF phase noise. Similar scans were carried out with the beams in collision and observing the luminosity in the Belle experiment (see Figure 11). The luminosity is recorded as a function of RF phase noise while exciting the LER and HER CCs individually. First visible effects appear at −70 dBc, which corresponds to about 0.03°. This value can be extrapolated to the LHC CC tolerances as a high ceiling, i.e. the LHC cavity phase noise must be smaller than 0.03° since radiation damping in LHC is almost negligible. Strong-strong beam-beam simulations (3D) were carried out to study phase noise effects and emittance growth of colliding beams with a local crab compensation at IP5 in the LHC ($\beta^* = 0.25$ m, $\theta_c = 0.522$ mrad). These simulations indicate a tolerance of $0.02\,\sigma\,\tau$ for 10 % emittance growth per hour, where σ is the transverse offset and τ is the correlation time. This is approximately consistent with KEK-B experiments. Weak-strong simulations with a phase error at varying frequencies observed from the KEK-B cavities were performed (see Figure 12). For the highest frequencies (32 kHz), the resulting dynamic offset collisions yield a tolerance of $\leq 0.1\,\sigma$ to control the emittance growth below 10 % per hour. With the low-level RF technology it should be feasible to meet the tolerances but more simulations are needed to accurately define the specifications. It should be noted that the phase noise tolerances will be additionally relaxed due to luminosity levelling as the crab voltage maybe smallest when the beam-beam parameter is at a peak.

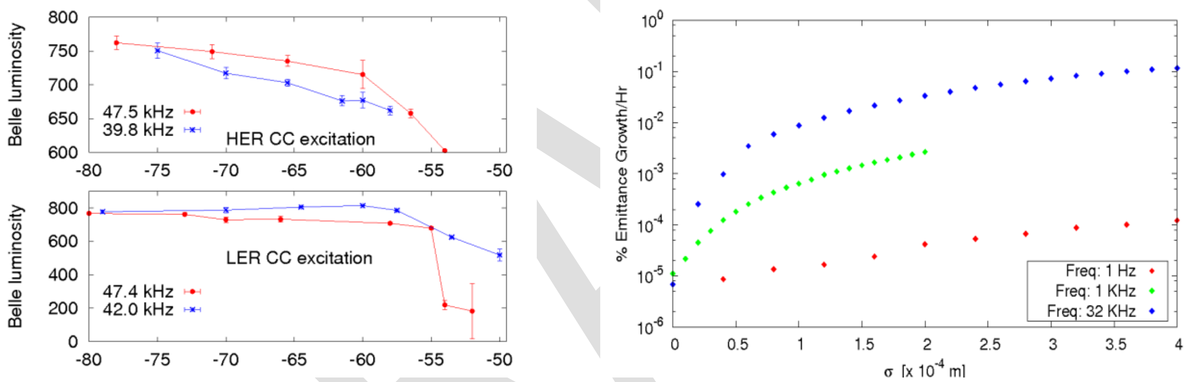


Figure 12. Left: Luminosity degradation as a function of noise amplitude at two different noise frequencies. Right: Emittance growth from weak strong beam-beam as a function of noise amplitude at different frequencies corresponding to observations from KEK-B cavities.

4.2.5 Collimation Efficiency and Hierarchy

Collimation efficiency is a serious concern for LHC beams. The impact on collimation with the existing collimators setup in IR 3 and IR 7 is minimal for a local scheme. For a global scheme, studies were carried out with a single crab cavity placed in the IR 4 region to achieve head-on collisions at IP 5 [Yipeng]. As a non-adiabatic increase in crab cavity kick results in emittance growth, the cavity voltage is ramped over 1000 turns after which the collimators are input in the tracking simulations. Results show no observable difference in the loss maps between nominal LHC and that with global crab cavities (see Figure 13).

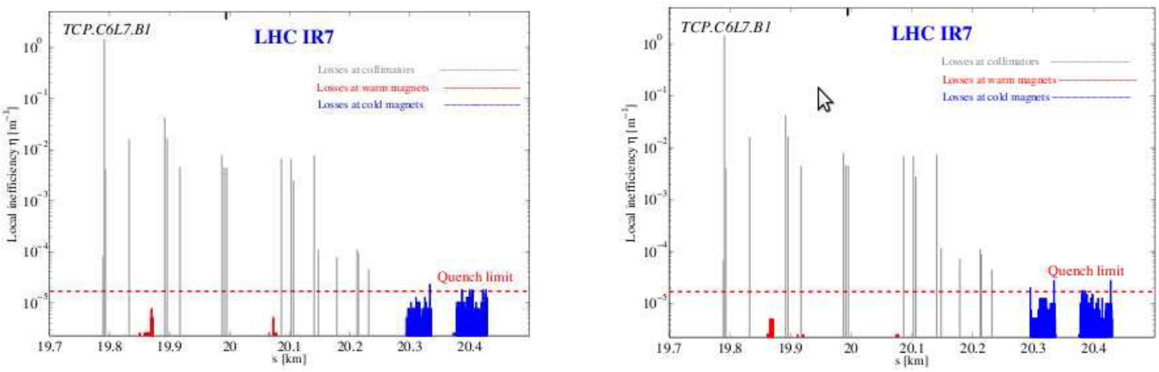


Figure 13: Loss maps around the LHC ring with the cold region marked in blue. Nominal LHC (left) and the case with a single global crab cavity placed in IR4 (right) are shown.

A phase space cut of all collimators was constructed as a function of the effective δp (with δz set as 1σz) in the presence of crab cavities to determine the allowed region for beam. The constructed phase cut is similar to the one of the nominal LHC (see Figure 14) and maintains the hierarchy of the primary, secondary and tertiary collimators critical for efficient collimation. Dynamic aperture (DA) studies were also carried out and no significant impact was visible. A maximum decrease of 1 σ was calculated for the global crab crossing scheme (nominal DA 13 σ). In addition suppression of synchro-betatron resonances was clearly visible.

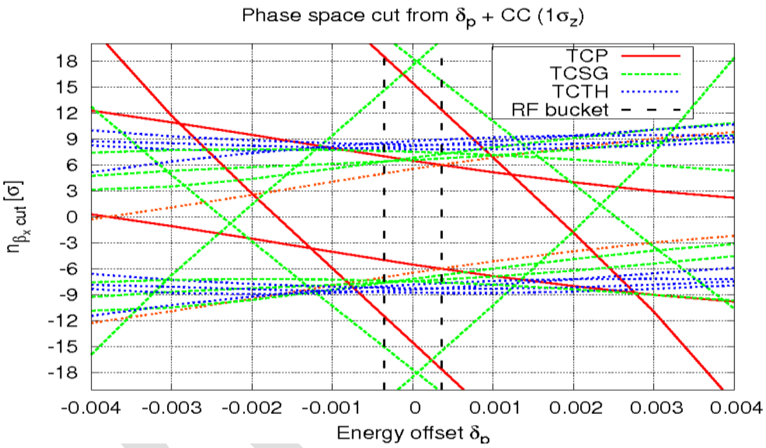


Figure 14: Phase space cutoff all collimators in the LHC with globally crabbed beams in the LHC with nominal optics. The hierarchy of the primary (red) secondary (green) and tertiary (blue) are maintained as in the nominal case without crab cavities.

5 Towards a Full Crab Crossing in LHC

The final goal of a full crab crossing scheme in the LHC is to obtain a significant luminosity increase by installing local crab cavities in IR5 and IR1. This installation will be a part of the revised luminosity upgrade described above, following the planning of Figure 1, i.e. by mid 2021. This requires four compact cavities for each IR, two per beam on either side of IP. All cavity and associated equipment have to be fully commissioned and ready for beam with ultimate intensities in mid-2021 as given in the planning of Figure 1. An overall strategy to realize this goal is presented in this section. Following the general plan for the HL-LHC project proposal, the crab cavity project is divided three phases. A first phase concerns the RF design and cavity prototyping to validate the performance of the compact cavity candidates by the point of the TDR. A second phase concerns the subsequent fabrication of pre-series cavities and all the related components and the infrastructure and preparation for SPS for beam tests and the use in LHC. The third phase will undertake the production of up to 10 cryomodules for the final installation in the LHC and the integration with the inner triplet upgrade. The first two phases are described in later sections.

5.1 STRATEGY

A strategy for the development of crab cavities for LHC is proposed along two fronts:

The **main goal** is to develop **compact crab cavities (CCs)**, compatible with a **local scheme**. The development of compact CCs constitutes a substantial R&D program. The cavities should be compatible with the nominal beam separation of 194 mm. They would be installed upstream and downstream of the interaction points. Compact CCs have to work at a harmonics of 40 MHz. Therefore, cavities operating at 400 MHz, the main RF frequency, are being considered. First design ideas for compact CCs exist, but many design and RF issues remain to be solved for these unconventional structures. These include achieving a design compatible with SC technology allowing the required field to be reached, avoiding multipactor, and having sufficient damping of unwanted cavity Lower, Same and Higher Order Modes (LOM, SOM and HOM). None of the present design proposals can at present be guaranteed to meet all the requirements. An intensive R&D program with prototyping is therefore mandatory. The risk of not achieving a viable design until too late in the project can be mitigated by preparing a second solution in parallel. This solution aims at a **global scheme** with **conventional** "elliptical" **crab cavities.** An active R&D program over the last years by US-LARP, EuCARD and at KEK has brought this concept to reasonable maturity today, so that the solution proposed could be considered for a shorter scale **production/implementation** program. These CCs would be installed near IR4, where the beam separation is enlarged to 420 mm, just compatible with a conventional elliptical cavity operated at 800 MHz. For cavities of this type, the SC RF technology has been developed successfully and optimized over the last decades, with solutions for the previously mentioned issues clearly identified. The cryostat and frequency tuners for such a system is conventional similar to existing cryostats e.g. the LHC design. The concentration of the CCs near IR4, where all LHC RF equipment is located, would ease installation and operation significantly. The locations previously intended for the ACN200 (200 MHz capture cavity) system are well suited; recent studies indicate that the ACN200 system may not be needed in the LHC, particularly if the proposed upgrade of the SPS 200 MHz RF system is approved.

Assumptions specific to the global scheme: At present, there is horizontal crossing at P5 (CMS) and vertical crossing at P1 (Atlas); we assume that the crossing plane can be made equal in both these main interaction points. We further assume that the beta-function in the crossing plane can be made large enough (around 2 km) at the CC location near P4. We also assume that the condition for betatron phase advance between the CC and the IP's can be met – this puts some constraints on the optics in the IRs and any compensation assumed between the IRs.

5.2 MITIGATION OF RISKS

The addition of crab cavities to the LHC should ensure a robust functioning through the entire sequence of the LHC physics cycle. The cavities should have no effect on the LHC beam during the injection, energy ramp and beta-squeeze at top energy. Since RF structures yet to be realized are conceived for the crab crossing, any tests with the hadron beams will enable to identify potential risks and device appropriate mitigation techniques to ensure safety of the accelerator.

5.2.1 PROOF OF PRINCIPLE IN SPS

An important and essential milestone is to test a crab cavity in the SPS, in order to verify that crabbing can be achieved in a proton machine, that there are no major 'showstoppers': i.e. there are no severe operational constraints and to demonstrate that the important issue of machine protection in LHC can be resolved. This should be done at the earliest opportunity. An SPS test can be done with a recuperated existing KEK-B 510 MHz cavity. Recently, a working group at CERN [14] has investigated the possibility of a beam test of the KEK-B 510 MHz crab cavity in the SPS. A suitable location currently hosting the COLDEX experiment, with cryogenics availability, was identified. This location is uniquely equipped with a Y-chamber bellows that allows for an insertion of the cavities only when needed for beam tests (see Figure 15). Some preliminary machine tests (e.g. on horizontal emittance growth and beam lifetime) are planned for machine experiments in 2010 at 55…120 GeV to confirm the usefulness of such a test. Conclusions of this investigation are directly relevant also for possible future testing of new LHC crab cavities in SPS. CERN is expected to confirm by the end of 2010 if it wishes to test the KEK cavity in SPS taking into account the relevance for such a test and the necessary effort and resources. An alternative would be to perform the SPS test with a dedicated conventional elliptical cavity at the more convenient frequency for SPS of 800 MHz. The latter could of course also be used in LHC for a global scheme at IR4. These cavities could also benefit from the power sources developed the existing SPS 800 MHz RF system (TWC800). It is expected that the 800 MHz conventional cavities would deliver a deflecting voltage that is at least a factor of two larger than the KEK-B cavities, along with easier integration into the SPS ring. A modification to a planned LHC collimator in the SPS would allow for dedicated collimator studies with crabbed beams.

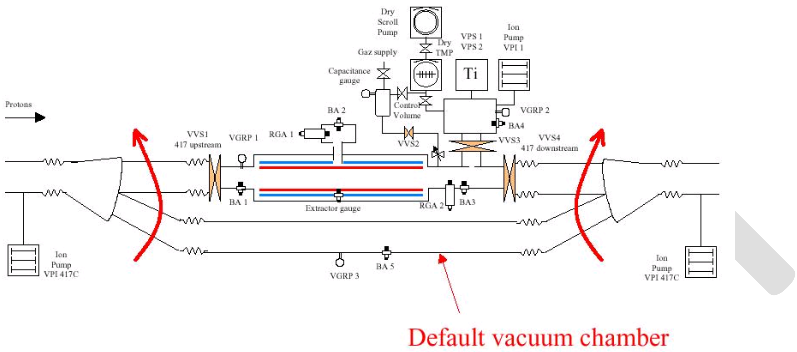


Figure 15: COLDEX location in LSS4 showing the Y-chamber bellows for insertion of the experiment into the SPS beam only for beam tests.

5.2.2 TESTING OF FINAL CAVITY DESIGNS IN SPS

Once a CC of either family would available, beam tests is first envisioned in the SPS. These tests will validate the individual cavity performance and avoid any loss of integrated luminosity in the LHC due to excessive commissioning time or operational difficulties. A common cryostat platform and modular design will enable easily installation and removal of cryomodules into the SPS for test purposes. Cryogenic investigation and planning is required to ensure the availability of adequate 2 K and 4 K Helium at the location of the COLDEX. An existing refrigerator can be recuperated to provide 4 K Helium.

5.2.3 COMPACT CAVITY DEVELOPMENT RISKS AND ITS MITIGATION

The risk of not achieving a viable compact design until too late in the project is to be mitigated by preparing a second solution in parallel. This solution aims at a **global scheme** with **conventional** “elliptical” **crab cavities.** An active R&D program over the last years by US-LARP, EuCARD and at KEK has brought this concept to reasonable maturity today, so that the solution proposed could be considered for a shorter scale **production/implementation** program. These CCs would be installed in IR4, where the beam separation is enlarged to 420 mm, just compatible with a conventional elliptical cavity operated at 800 MHz. For cavities of this type, the SC RF technology has been developed successfully and optimized over the last decades, with solutions for the previously mentioned issues clearly identified. The cryostat for such a system is conventional similar to existing cryostats e.g. the LHC design. The concentration of the CCs in IR4, where all LHC RF equipment is located, would ease installation and operation significantly. The locations previously intended for the ACN200 (200 MHz capture cavity) system are well suited; recent studies indicate that the ACN200 system may not be needed in the LHC, particularly if a proposed upgrade of the SPS 200 MHz RF system is approved [30].

6 STUDIES AND PROTOTYPING UP TO TDR

6.1 MACHINE PROTECTION

From the working group at CERN o study the feasibility of the KEK-B crab cavities concluded that SPS tests should mainly be used to make observations. No SPS interlocks are foreseen to be implemented for the near term. However, there could be two kinds of interlocks foreseen: slow (on BPMs) and fast (on RF). It might be possible in 2011 to have a BPM interlock post-mortem, i.e. the last 1000 turns, to study the effect on trajectories in case of problem. It should be noted that the SPS BPM resolution may not be sufficient for the type measurements foreseen. In the ideal case, a fast RF interlock would be required.

Another effect to be studied is the dependence of the RF phase on the Q_{ext} to avoid rapid phase changes during a RF trip. However, the Q_{ext} of the KEK-B cavities are fixed and it would require a major physical intervention to perform such a study which may not be in the scope of the SPS experiments. Operationally, it is preferred to have a low Q_{ext} (10^5), as in this case the cavity frequency is less sensitive to perturbations. However, it is assumed that machine protection may benefit from a high Q_{ext} to help avoid fast reaction on the frequency and phase of the crab cavity. Consequently, the cavity will be more sensitive to vibrations and external perturbations which could potentially lead to variations in the transverse impedance.

For the SPS measurements, potential ideas consist of increasing the crab cavity voltage to study the scaling of the trip rates with the RF voltage. The scan the synchronous phase, and the horizontal beam offset, and observe the effects on the beam to define limits of synchronous phase shift and horizontal beam offset.

6.2 SPS TEST OF KEK CAVITY

A proposal during the 2009 crab cavity workshop (LHC-CC09) to study the feasibility of using KEK-B crab cavities in the SPS was studied by a working group at CERN [14]. No real showstoppers were identified. However, many issues remain to be studied in detail for acquisition, integration and commissioning in the SPS. The best location for the KEK-B crab cavity seems to be the location of COLDEX.41737 experiment, which is not used anymore and can be removed. The two main reasons for this specific location are the large space (a cavern is required as the crab cavity is too big to be in the tunnel without perturbing the transport) and the available cryogenics required for the superconducting crab cavity. A first estimate on the time to remove COLDEX is approximately 2-3 weeks. A first cost estimate to change the PLC and for the supervision of the old cryogenics system (TCF20) is approximately 200 kCHF. The added advantage of the COLDEX region is the Y-Chamber bellows which allows for remote insertion of the crab cavity into the SPS beam only when needed for tests. This will ensure no additional impedance increase in the SPS due to the crab cavities and should present no perturbation to regular operation.

Four cavities were built at KEKB in collaboration with Mitsubishi, two for the LER and HER with two spares. The LER cavity has suffered field degradation, and has a tuner problem, hence the SPS tests would prefer the HER cavity. KEKB upgrade will use a 'micro-crossing' scheme – going for a 10x luminosity increase, but without crab cavities. CCs need to be taken out to avoid HOM problems at higher intensity.
The current Cavity specifications are: 1.4 MV deflecting voltage at 4.2 K operation. Static losses stand at 30 W and RF losses at 40 W. Coaxial HOM coupler placed in the centre of cavity is also used for frequency tuning and uses a significant part of cooling capacity. Total cryo load is approximately $\sim$ 100 W.

The crab cavity will be used in KEKB until June 2010. The KEK-B cavity will have to be removed from the tunnel, physically modified to be tuned to a frequency of 511 MHz (instead of 509 MHz) and possibly a high Q_{ext} (changing the coupler) to be compatible for SPS. The cavity will be dismantled in a clean room and stretched to tune to the appropriate SPS frequency. A high pressure rinse maybe needed to remove any contaminants during the dismantling and frequency tuning process. The work will be primarily performed by Mitsubishi with some CERN support. Any tests on cavity performance maybe best to perform at CERN in a vertical cryostat as reassembly will take place at CERN to minimize damage to the cryomodule assembly while transport. A preliminary estimate for modifications, transport and reassembly is approximately 1 year and installation in the SPS could be optimistically completed at the end of 2012 at the earliest. A detailed schedule and cost estimate is being compiled [31]. The SPS tests should be scheduled with the foreseen with the running of the injector complex.

The KEK-B cavities require approximately 200 kW in their current configuration. However, if the Q_{ext} is increased, this power requirement could be reduced by a factor of two or more. For the higher Q_{ext} case, IOT(s) could be used in series to provide the power but needs investigation. The space for the RF power sources and other infrastructure also needs a detailed study to ensure proper installation. As the crab cavity will be transported from Japan, modifications after the retuning of the cavity and reassembly on CERN site will be most appropriate. This will ensure any cavity alignment inside the cryostat and allow for reprocessing if any gradient degradation is observed during transport. A potential RF test location for the KEK-B cavities could be SM18 as it already has the necessary cryogenics infrastructure. However, RF power at 511 MHz is not available and needs additional installation.

An approximate cost estimate on the cryomodule preparation, infrastructure, RF, cryogenics and support is given in Table 3.

Table 3: Preliminary cost and resources estimates for KEKB cryomodule preparation and installation in the SPS.

Item	**FTE**	**kCHF**
Cavity-coupler preparation (at KEK)		300
Transport		50
Re-assembly		600
Cryomodule preparation (items above)	***1***	***(1000)***
SM18 modifications & infrastructure		100
RF power plant – 500 MHz	1	400
Controls, LLRF & Instrumentation in SM18	1	200
Power testing and processing	0.2	50
Vacuum preparation in SPS	0.5	100
Controls, LLRF in SPS	0.5	150
Cryo in SPS (controls upgrade)	1	200
Cabling and infrastructure	0.3	200
Processing and commissioning in SPS	0.3	100
MD Support (OP, RF, Cryo, ABP)	2	0
Totals	**7.8**	**25000**

6.3 Beam Studies

Beam studies in the SPS aims to study the effects of deflecting cavities on high energy beams to distinguish between protons and electrons. Prior to installation of deflecting cavities in the SPS, KEK-B cavity being the earliest, studies in the SPS to determine the appropriate beam conditions and measurement devices to accurately perform the experiments with deflecting cavities.

6.3.1 Impedance & Instabilities

Accurate knowledge of the impedance from the crab cavities and tolerances for damping will be vital to understand the stability thresholds for nominal and ultimate beam currents in the LHC. Both bench measurements and beam measurements in the SPS will enable a clear characterization of the cavity impedance and consequently the required damping to stay below the instability thresholds. Impedance measurements using intensity dependent tune shift measurements have been carried out for several years to measure the total machine impedance and understand the contributions of the various elements. Additional measurements before the installation of the deflecting cavities maybe performed to accurately determine the additional impedance from the deflecting cavities. New "localized" techniques maybe needed to increase the sensitivity of the measurements and propose any required improvements to measurement devices.

Two long-range beam-beam wires are installed in the SPS with which several long-range experiments have been carried out in the past years [32, 33]. These wires could potential be used to induce an artificial long-range interaction in the presence of the crabbed bunches to study the effects. A distance and current scan of the DC wires could be carried out at different energies with and without crab cavities. Other non-linearities like octupoles can be introduced to enhance the effects if needed.

6.3.2 RF Noise and Stability

An important measurement is the effect of the RF noise on the beam emittance. A beam with good natural emittance and lifetime (and not only the usual beam current lifetime) is a requirement for such a measurement. Furthermore, the tilt from the crab cavity should be at least of the order of the horizontal beam size to see observe the effect of the crab cavity. Therefore, beam parameters with a rms. normalized emittance of $\sim 2\ \mu$m and a beam momentum of 55 GeV/c would be ideal. It is proposed to perform experiments in the SPS to study the natural emittance lifetime in coast. Beam energies of 55 or 120 GeV/c, without a crab cavity and with few bunches will be tested as a first step. This will be followed by experiments with few batches to introduce RF transients and other effects, spaced by $4 \times 24.95 = 99.8$ ns which are compatible with a frequency of the crab cavity of 511 MHz). The preparation of the 100 ns bunch spacing beam is already in foreseen for the ALICE experiment. A parametric scan of the RF noise amplitude and frequency is anticipated to comprehensively study the evolution of the beam size to establish tolerances for the LHC crab cavities.

6.3.3 Collimation

As efficient collimation is a vital issue, a planned 2nd collimator (from SLAC) proposed to be installed in the SPS in 2010 or 2011. The best location for the SLAC collimator was studied and a proposal from the crab cavity working group was made. It should be noted that both collimators in the SPS are in the horizontal plane which is also the anticipated plane of crossing. With the proposition, the phase advances are such that almost no crab effect is seen at the 1st (SLAC) collimator, whereas the full crab effect is seen at the second (CERN) collimator. This allows for dedicated collimation experiments to determine efficiency, beam losses and hierarchy of the collimator system is a pseudo primary-secondary configuration as in the LHC. However, to do so the vertical Ionization Profile Monitor needs to be moved before the QD.517.

6.3.4 Optics Considerations

Preliminary simulations have been carried out using the BBSIM code to investigate the effects on emittance growth and beam losses in the SPS with crab cavities. A KEK-B type cavity placed at the COLDEX region at a frequency of 509 MHz and 1.5 MV transverse kick voltage was used to perform these simulations. The emittance was found to blow up due to non-zero dispersion and derivative of the dispersion function at the location of the COLDEX. The cavities were moved to 90 m upstream to a location with small dispersion and the emittance growth was found to be less than 20%. It should be noted that the nominal horizontal tune is placed on the 8^{th} order resonance in the presence of non-zero dispersion leading to this emittance growth [34]. A small change in the working point above or below the resonance should avoid this emittance growth and studies are underway to determine the best working points for the crab cavity tests in the SPS. With aid of the BPM system and crab cavity phase variations, the "crab-dispersion" can be measured and compared to model as performed in KEK-B.

The KEK-B cavities are limited to a maximum of 2 MV transverse kick. The proposed location, COLDEX, has a horizontal beta-function that is smaller than in the other parts of the machine. If the voltage of the cavity is insufficient for the proposed experiments, dedicated quadrupole power supplies (2…4) maybe required to create local optics knobs to enhance the beta-functions near the location of the crab cavity. This will enable experiments to exploit the full energy range of the SPS (26…450 GeV). If LHC cavities (conventional or compact) become available with a larger kick voltage, this modification may not be necessary.

6.3.5 Operational Scenarios

Some operational scenarios concerning single-beam issues envisioned in the LHC can be tested in the SPS. The current operation in KEK-B uses injection of beam at top energy with the cavities at nominal voltage. For the LHC, the cavities will be at "zero-voltage" (but with active feedback) to be invisible at injection and energy ramp. Therefore, accumulation of beam with "zero-voltage" in the SPS will be tested. Other issues related to beam loading and transient effects with and without RF feedback & orbit control will be attempted to study the stability and tolerances on the feedback systems.

Induced RF trips and its effects on the beam will be studied in detail to guarantee machine protection and devised appropriate interlocks. Long term effects with crab cavities on coasting beam at various energies will also be tested.

6.4 Specification of Cavity Performance

The conventional two-cell cavity at 800 MHz is expected to operate at a nominal 2.5 MV transverse kick voltage. This corresponds to surface electric and magnetic fields are 25 MV/m and 83 mT respectively which are well below the state-of-the-art surface fields achieved in SRF cavities used for acceleration. The experience of the KEK-B cavity also points to the limitations above these surface fields, but the exact origin of the limitation in the KEK-B cavities are perhaps specific to the coaxial beam pipe coupler. The bare cavities should perform well above the 2.5 MV (+50%) to allow for any degradation due to assembly into cryostat with multiple couplers and sufficient operational margin. In addition, the Q_0 of the cavity at the operating field should at minimum exceed 10^9 to avoid excessive cryogenic losses. If buffer chemical polishing is insufficient to provide the field gradient at the reasonable Q_0, electro-polishing should be employed.

For compact cavities, the concepts are vastly different with different performance limitations defined by the field configuration and geometry. Therefore, a minimum specification similar to the conventional cavity is adopted. Since the compact cavities are expected to operate at a lower frequency to alleviate RF curvature issues, the effective voltage performance compared to the conventional cavities operating at 800 MHz should be increased by a factor of two [5]. Therefore, a nominal voltage of 5 MV transverse kick is assumed for compact cavities operating at 400 MHz Some of the compact cavities have significantly favourable surface field to kick voltage ratio, they should perform better than the conventional counterpart for a given structure length.

6.5 Compact Cavity Prototyping

The conceptual design of the various compact cavities needs completion. An initial down selection based on the achievability of the performance specifications is envisioned. At least two of the designs must reach this stage. Frequency tuning concepts need to developed and taken into consideration during the down selection as the LHC cavity has to compatible with the vast range of the energy ramp of the LHC. **Valid**

conceptual designs for the **SOM, HOM and LOM couplers** and for the **helium tank** would also be needed at this point. On the down selected options the work would continue on a number of items:

1) Completion of a full technical design with mechanical drawings and specification.

2) Construction of prototypes (possibly in copper initially) to develop manufacturing techniques and tooling.

3) Fabrication of a niobium cavity

4) Cleaning and electro-polishing would then be done on the bare niobium cavity. (i.e. no couplers, antennas or other accessories).

5) Cavity surface inspection and instrumentation (cryogenic, RF and vacuum) needed for the cavity tests for the complex shapes needs to be developed.

6) Low power tests and measurements on the bare cavity would follow in a test cryostat to check that the cavity performs to the gradient specification and stable ramping is feasible. A mock-up tuning mechanism maybe required to test the frequency tuning of the cavity with RF power.

Initial studies on cryostat design for compact cavities should be started, not yet necessarily focusing on a particular cavity design.

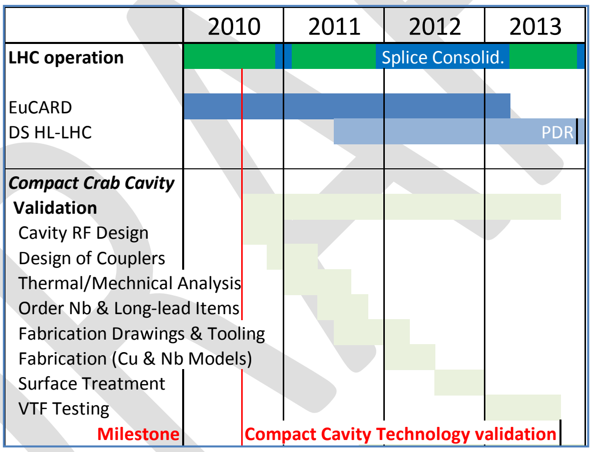


Figure 16: A possible schedule for the validation phase for compact crab cavities

6.6 Compact Cavity Design Selection

At this stage a decision would be made on the final compact cavity design to be retained for series production, should there be more than one contender.

6.7 Conventional Elliptical Cavity

It is essential to retain a conventional cavity option in the unlikely event of a major unforeseen difficulty with compact cavities. Use of conventional designs would entail significant civil engineering costs and use of dogleg sections in the IRs, but this would still be acceptable, in view of the value of gaining back significant luminosity from the crossing angle. A straightforward conventional cavity installation in IR 4 as a global scheme would serve as an alternate option in the worst case. To this end, for the TDR, **a full mechanical design of the elliptical cavity, its accessories** and the **elliptical cavity cryostat** must be prepared.

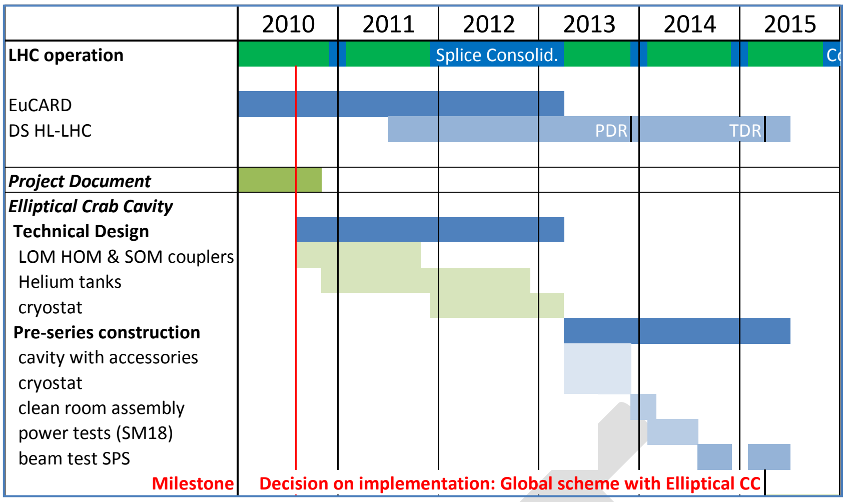


Figure 17: A possible schedule for the design and pre-series phase of elliptical crab cavities.

7 Activities and Planning for Construction

The post-TDR phase will consist of constructing a conventional and a compact cavity for a pre-series cryomodule. The technical design of power couplers, HOM couplers and antenna probes for the final down selected CC option must now be completed, and construction and testing of these components carried out. An ongoing cryostat design study should then focus on the final design, leading the way to construction and test of a pre-series cryostat. The cavity and its accessories would be installed in this cryostat, to make a pre-series cryomodule, ready for test and power processing.

7.1 Conventional Elliptical Cavity Design

Although the elliptical cavity operating at the TM_{110} deflecting mode is validated in KEK-B machine, the 800 MHz design conceived for the backup solution requires prototyping. The addition of a second cell and its effect on the cavity performance and the differences in the coaxial damping system requires validation. The prototype help validate all design issues, in particular, the approach taken to simplify the coaxial damping scheme with only vertical couplers will be studied in detail for its RF, thermal and mechanical performance. The addition of groove to the cavity iris to suppress some multipacting issues also requires testing at high field and superconducting temperatures. It will also help set a baseline specification for the compact candidates which are anticipated to follow after the pre-series conventional cavity production.

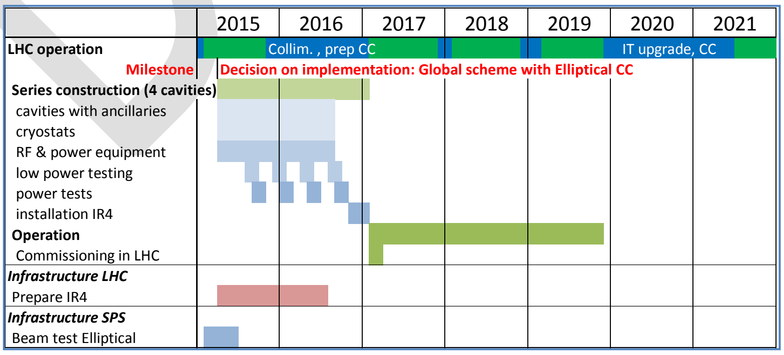


Figure 18: Possible schedule for the construction of elliptical cavities for installation in IR4.

7.2 Construction and Test of a Pre-series Compact Cavity Cryomodule

The main activities (work-packages) to be foreseen are:

1) The full technical design of the SOM, HOM and LOM couplers.

2) The full technical design of the helium tank, in accordance with CERN safety norms

3) A complete tuner design and the integration into the cryostat

3) The full technical design of the cryostat

4) The construction of a pre-series cavity with its accessories and instrumentation

5) Construction of a pre-series cryostat.

6) Clean room assembly of the pre-series cavity in the cryostat.

7) Power testing of the resulting completed pre-series cryomodule in a dedicated test stand, such as CERN's SM18.

8) **A full beam test of the complete pre-series cryomodule in SPS.**

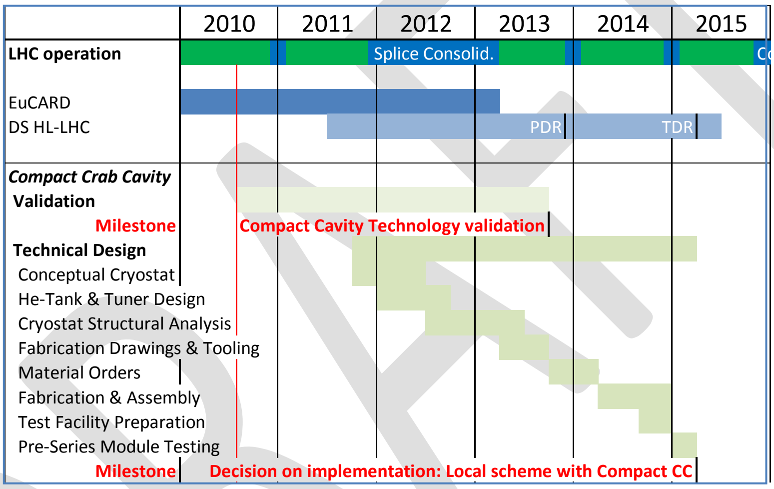


Figure 19: A possible schedule for the pre-series of compact crab cavities for tests with beam in SPS.

7.3 Construction and Test of Series Cryomodules

The main activities (work-packages) to be foreseen are:

1) Launching series production of cavities, couplers and other cavity ancillaries

2) Launching series production of cryostats

3) Launching series production of RF and power equipment

4) Low power testing of series bare cavities

5) Clean room assembly of series cavities and their ancillaries in their cryostats

6) Power testing of the completed series cryomodules in the dedicated test stand.

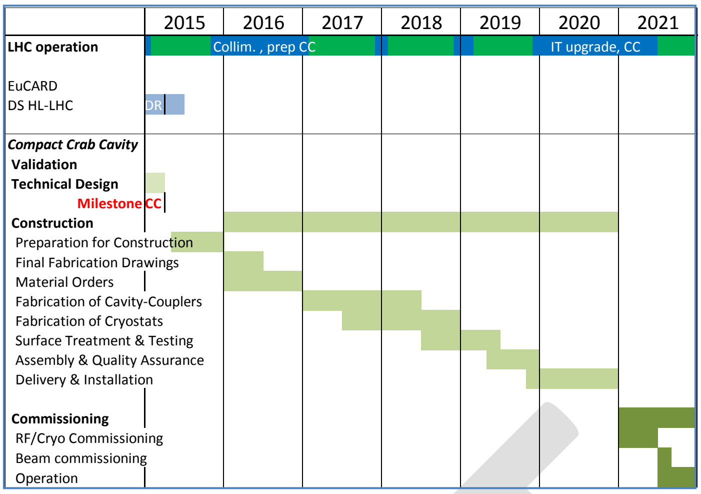


Figure 20: A possible schedule for the construction of 8+2 cryomodules with compact crab cavities.

7.4 RF Power

7.5 Cryogenics

7.6 Low Level RF

7.7 LHC Integration

7.8 Hardware Commissioning

7.9 Beam commissioning

8 Deliverables, Planning and Cost Estimate

The relevant deliverables, critical milestones and planning are presented. Also a summary of Risk analysis and mitigation measures. Critical tasks for Phase 1 (TDR), then all the activities needed for Phase 2 and commissioning. Planning and cost estimates…

8.1 Deliverables for the TDR

'Proof of Principle' document concluding on machine protection, beam studies, Impedance, RF noise, stability, emittance blow up…:

- Full mechanical design of the elliptical cavity, its accessories and cryostat,
- Final / full specifications on compact cavity and performance,
- SPS Test of KEK cavity,
- Completion of conceptual compact cavity designs and a first down selection made based on the achievability of the performance specifications. At least two designs must reach this stage.
- Valid conceptual designs for the SOM, HOM and LOM couplers,
- Conceptual design for the CC helium tank,
- Construction of prototype cavities for the retained CC designs,
- Low power tests and measurements on the bare cavity,

- Decision on the final retained cavity design,
- Specifications for RF equipment and cryogenics.

8.2 Construction and Test of Cavities and Cryomodules

Deliverables and milestones related to the series production of cavities, ancillaries and cryomodules:

- Completion of specifications for cavity production, couplers, cryostats and other components,
- Launching series production of cavities, couplers and other cavity components,
- Launching series production of cryostats,
- Launching series production of RF and power equipment,
- Successful low power testing of series bare cavities,
- Completion of clean room assembly of series cavities and their ancillaries in their cryostats,
- Successful power testing of the completed series cryomodules in the dedicated test stand,
- Test in SPS of a completed CC cryomodule.

8.3 Conventional Elliptical Cavity Construction

To be done only if compact CC designs proved not to meet the targets (?)

Work-packages:

- Bare cavity construction & test,
- couplers design,
- SOM, LOM, HOM damper construction,
- cryostat design,
- cavity construction and assembly,
- Elliptical cavity power testing in cryostat,
- test in test area,
- SPS test.

8.4 Procurement and Installation of Other Systems

8.4.1 RF system – RF Power, LLRF

8.4.2 Cryogenics

8.4.3 Controls

8.4.4 Infrastructure

8.5 Installation in LHC and Commissioning

8.6 Overall Planning

(Gantt Chart – based on the above + Rama’s details to fold in)

8.7 Cost Breakdown

Table 4 gives an initial estimate of the necessary budget and human resources for the project.

Table 4: Preliminary resource estimate (table has to be filled with numbers for open items!)

Project "Crab Cavities for the LHC"	resource type	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Σ
Total Project	Σ FTE	3.4	9	9.9	13.2	12.5	9.4	3.8	2.85	3.1	2	1.3	70
	Σ MCHF	1.01	4.55	7.87	8.83	10.24	5.86	5.47	6.39	6.52	6.84	5.68	69
	Attention, the above sums do not (yet) reflect the totals for the project!												
Project coordination													
Total Project coordination	Σ FTE	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	3
	Σ MCHF	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0
Studies (chapter 6)													
Total Studies	Σ FTE	2	2	2	2	2	2						
	Σ MCHF												
KEK-B CC test in SPS													
Total KEK-B CC test in SPS	Σ FTE												
	Σ MCHF												
RF power systems													
Total RF power systems	Σ FTE												
	Σ MCHF												
RF Low-level and controls													
Total RF low-level and controls	Σ FTE												
	Σ MCHF												
New cyoplant LHC IR4													
	Σ FTE		3	3	6.5	6	3.5	2	1				25
	Σ MCHF		1.65	4.4	4.4	5.5	2.75	1.1	0.5				20
Infrastructure LHC													
	Σ FTE												
	Σ MCHF												
Infrastructure SPS													
	Σ FTE												
	Σ MCHF												
Elliptical Crab Cavity													
Total Elliptical Crab Cavity	Σ FTE	1	2	2	3	3	1						12
	Σ MCHF	0.5	2	3	3	3	2						14
Compact Crab Cavity													
Total Compact Crab Cavity	Σ FTE	0.6	1.7	1.6	1.4	1.2	1.6	1.5	1.55	2.8	1.7	1	17
	Σ MCHF	0	0.89	1.46	1.42	1.73	2.1	4.36	5.88	6.51	6.83	5.67	37

Attention:
this table is not complete, many items, studies and subsystems have not yet been estimated.
WORK IN PROGRESS!

9 CONTRIBUTING PARTNERS AND PROPOSED WORK PACKAGE DISTRIBUTION

9.1 CERN'S ROLE AND RESPONSIBILITIES

CERN will perform the overall coordination & management synchronized the HL-LHC design study for the upgrade foreseen in 2020. In its role, CERN will ensure the compatibility with LHC hardware, safety standards and ultimate overall responsibility.

9.2 ROLE OF US CONSTRUCTION PROJECT

The goal of the High Luminosity LHC design study (HL-LHC) is to enable:

- Focusing of the beams to $\beta^* = 10 \ldots 25$ cm in IP1 and IP5 at ultimate intensities, with the aid of new high gradient and large aperture (Nb_3Sn) inner triplets in conjunction with crab cavities,
- Reliable and safe operation of the LHC at an average luminosity of $5 \cdot 10^{34}$ cm $^{-2}$s^{-1}, [for] the physics run in 2021 and beyond must be guaranteed.

The scope of the project is to:

1. Upgrade the IR regions of ATLAS and CMS compatible with the optics and technology envisaged for 2020 installation,
2. Replace the present inner triplet quadrupoles with high gradient and large aperture Nb_3Sn technology to focus the beam to $\beta^* = 10 \ldots 25$ cm in IP1 and IP5.
3. Install crab cavities in the IRs 1 and 5 to compensate geometrical reduction and enable luminosity levelling.
4. Modify other insertion magnets as needed to implement new optics and chromatic correction schemes.
5. Maintain safe and reliable operation with efficient collimation and machine protection at the upgraded beam currents and optics.

Several upgrades to the injector chain is being planned and implemented at CERN. The beam commissioning of the 160 MeV H- linear accelerator (Linac4) is expected to start in 2016. Linac4 will double the brightness and intensity of the output beam, removing the first injector chain bottleneck. Consolidation of the injector chain will ensure a reliable operation of the injector chain for the lifetime of the LHC. Furthermore, an energy upgrade of the PS Booster and the upgrade of the SPS to remove additional bottlenecks from collective instabilities will propagate the higher intensities efficiently towards the LHC, thus achieving higher average luminosities beyond 2020.

Taken together, these projects will provide an average luminosity $5 \cdot 10^{34}$ cm $^{-2}$s^{-1} and thus moving towards the final goal of 3,000 fb^{-1}.

CERN plans to release a HL-LHC Preliminary Design Report (PDR) in 2013 and a final Technical Design Report (TDR) in 2015 to define the exact upgrade path for 2020-21. The US collaborators within the framework of US-LARP and other SRF activities are in a unique position to rapidly advance the R&D of compact crab cavities which is a vital ingredient for the HL-LHC upgrade. Therefore, the US contributions on crab cavities will primarily focus on the development of compact cavity technology to exploit the full potential of the inner triplet upgrade with local crab crossing. The US contributions to the crab cavity R&D project will be fully integrated into the CERN overall planning for HL-LHC and the crab cavity work package within the design study. to achieve a pre-series cryomodule equivalent required before 2016 according to the present baseline path of HL-LHC. This vital step will determine the course of the civil engineering and installation procedures for the IRs 1 and 5. The major milestones for the crab cavity work package as envisaged for the HL-LHC upgrade are shown in Figure 2. A preliminary schedule for the R&D and construction of the technology enabling a local crab crossing scheme is shown in Figure 21.

The total cost of the US contributions will not exceed $30M. Initial funding in FY11-12 for a period of 3 years will help realize cavity validation phase to achieve a CD-0 status. A detailed project proposal with accurate project schedule, cost estimate and milestones, tied with the HL-LHC Preliminary Design Report, will be the deliverable at this stage. Project funding commencing in FY14-20 to first fabricate pre-series cryomodules, followed by the construction of 8-10 cryomodules to be installed and undergo hardware commissioning. The maximum funding rate will not exceed $5M in any fiscal year.

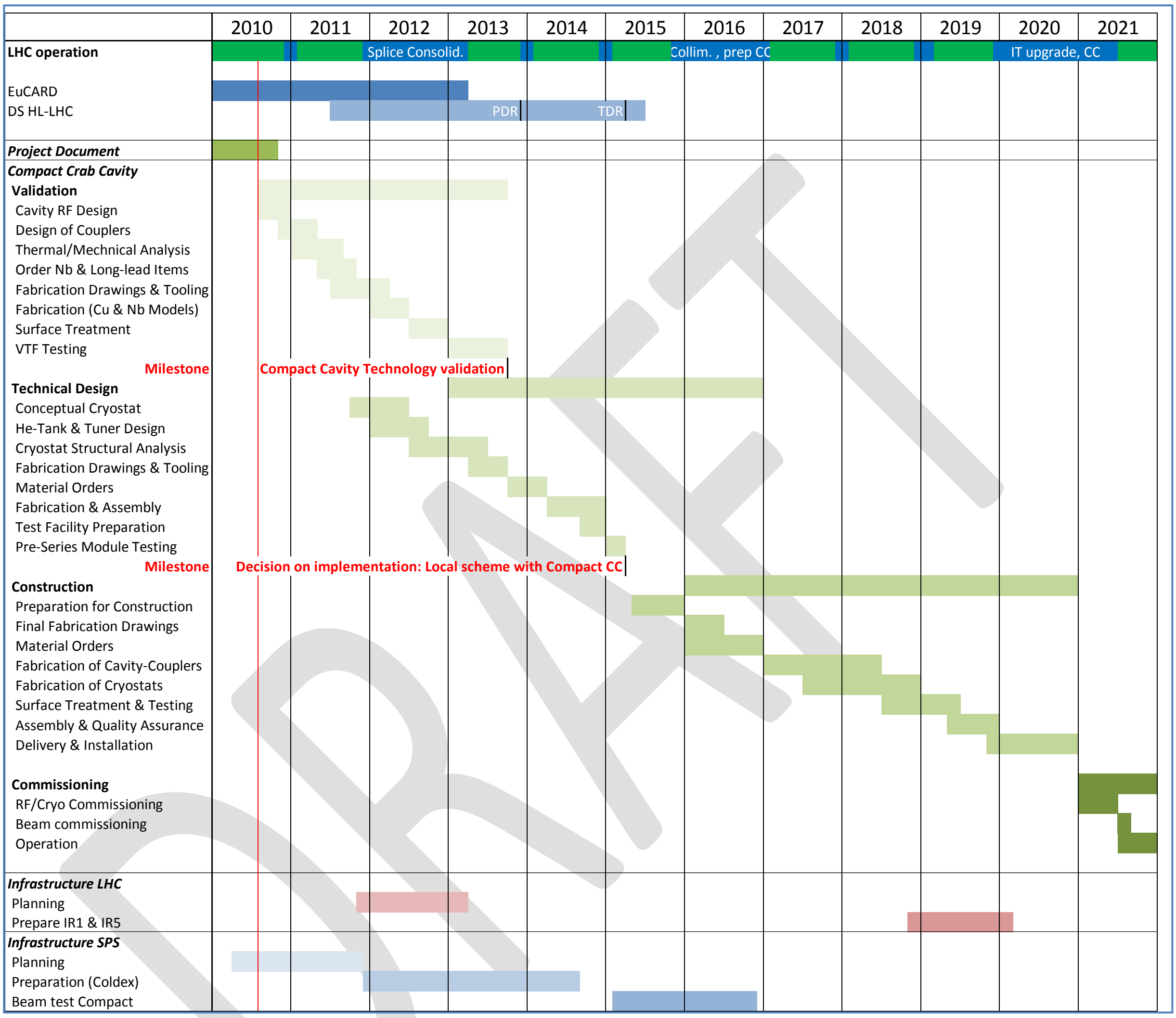


Figure 21: Overall planning concerning the Compact Crab Cavities

9.2.1 Initial Cavity R&D Phase, FY11-12

The deliverable for the initial phase of the cavity R&D will be a detailed project schedule, accurate cost estimate and milestones fully integrated with the HL-LHC design study. At this stage, compact cavity field validation tests may become available depending on the funding available. The following tasks are to be performed:

Jan	**2011**	Detailed RF design of the cavities and HOM damping schemes.
Jun	**2011**	Detailed thermal and mechanical analysis of cavity-coupler systems, Order Niobium sheets and related tooling.
Jan	**2012**	Finalize the cavity-coupler specifications for fabrication, **LHC is shutdown for splice repair.**
June	**2012**	Tooling and copper model fabrication,

		Testing on copper models (HOM damping, surface treatment etc.).
Jan	**2013**	Fabrication of the Niobium cavities complete, Preparation for surface treatment and instrumentation for 2 K testing.
Jun	**2013**	Surface treatment and testing of cavities at 2 K, Field validation, quench limits and related RF studies, HL-LHC PDR, Cavity review for launch of pre-series cryomodule.

9.2.2 HL-LHC TDR and US CD-2

Following the cavity review in summer 2013, a detailed project schedule and cost estimate will be made available for the fabrication of a pre-series cryomodule(s), tied in with the HL-LHC TDR in 2015 and leading up to the construction of the final 8-10 cryomodules ready for installation in the 2020-21 upgrade.

The following tasks are to be performed within the pre-series cryomodule phase:

Jan	**2014**	Detailed cryomodule design for the down selected cavity, Thermal and mechanical analysis, Tooling and orders placed for long lead items.
Jun	**2014**	Detailed technical design complete , All couplers, ancillary equipment and instrumentation finalized, Infrastructure and installation planning, **Cryomodule readiness review.**
Jan	**2015**	Fabrication and assembly of the cryomodule, Integration of the cavity, tuner and subsystems into cryostat.
June	**2015**	Fabrication complete and RF testing and processing, HL-LHC TDR, Field validation in a complete cryomodule, reliability tests.
Jan	**2016**	Installation into SPS and interconnections with cryogenics, **LHC/Injectors shutdown for LINAC4/Collimation.**
Jun	**2016**	RF testing at 2K in the tunnel and mechanical subsystems, Project schedule and cost to construct 8-10 cryomodules , **Cryomodule construction project review.**

These pre-series cryomodule(s) are expected to finish fabrication and RF testing will undergo beam tests in the SPS and/or the LHC depending on the shutdown schedule during the period of 2016 (see Figure 21).

9.2.3 US Construction Project

Based on the pre-series experience, the final technical design along with a detailed schedule and cost estimate to fabricate 8-10 cryomodules will be completed with final engineering specifications. All technical modifications required will be reviewed and carried out.

9.2.3.1 Compact Cavity Cryomodule

Technical advantage of cavities with smaller footprint and lower frequency are required for an IR upgrade with crab crossing. The successful construction and demonstration of the new class of crab cavities will set a benchmark for the performance of superconducting deflecting cavities in all accelerator applications. The US contributions could build up to 10 cryomodules hosting up to two types of cavities which satisfy the field and safety requirements of the LHC. Each cavity will be equipped with a fundamental power coupler compatible with the power requirements of the LHC crab cavity system. The tuning system must be robust in both fast and slow levels to operate in the energy range of the LHC robustly assuming the cycling of the machines during its operation.

The tight tolerances set by the LHC impedance budget demand strong damping schemes while simultaneously providing a robust cavity-coupler system that can cope with energy and intensity range of the LHC beams. Two or more HOM coupler will be required per cavity designed with sufficient cooling capacity for efficient extraction of HOMs.

All ancillary equipment such as the He-vessel, magnetic shielding and vacuum shielding will be designed in accordance with the pressure vessel code. All RF and cryogenic interfaces will be designed according to the CERN standards finalized after the pre-series cryomodule review. Surface treatment, assembly and transport systems will also follow the specifications finalized at the review.

9.2.3.2 Cryogenics and RF Interfaces

All cryogenic and RF interfaces (for example: waveguide connections) should be fully compatible with the CERN standards and fabricated to specifications. Technical specifications will be derived from the pre-series cryomodule tests to determine material standards for interfaces such as flanges and seals with the complex cavity-coupler system.

9.2.3.3 Instrumentation

Each of the 8-10 cryomodules will be equipped with variety of instrumentation to monitor physical, RF and cryogenic parameters. Since the cryomodule will be placed inside the beam line, remote alignment and operation is highly desired and will be made available if possible. Temperature sensors will be placed at all critical locations to monitor the temperature and superconductivity of the cavity-coupler systems. Vacuum instrumentation to monitor the degradation of the cavity and coupler vacuum is vital to maintain robust operation and efficiently detect failures related to crab cavity vacuum to maintain machine protection. Dedicated trajectory and loss monitors maybe required to minimize beam loading and detect fast changes in the beam trajectories to ensure safety of the LHC IRs and magnets. RF phase and amplitude detectors along with appropriate active feedback systems are vital for avoid any undesirable effects on the beam due to RF failure of the crab cavity. The low-level RF systems will be designed in close collaboration with CERN.

9.2.4 Schedule and Budget

A schedule, showing R&D starting in FY11 and construction starting in FY15 is developed (see Figure 2). This schedule allows for maximum flexibility in terms of time and available technology to realize the cryomodules proposed for the 2020/21 IR upgrade. The R&D serves a vital part in development of the complex technology within a time frame that is reasonable. It also allows for reconfiguration of schedule and technology choice based on the R&D results to optimize the resources. Highlights at the end of each fiscal year as follows:

- **FY11.** Complete RF design of the compact cavity concepts. Procurement of long lead items such as Niobium.
- **FY12.** Complete coupler designs and associate RF, mechanical and thermal modelling. Procurement of long lead items.
- **FY13.** Field validation of at least one compact cavity concept to LHC specification.
- **FY14.** Procurement of materials and tooling for pre-series cryomodule(s).
- **FY15.** Completion of pre-series cryomodule(s) with beam tests. Procurement of Niobium, couplers, and ancillary equipment.
- **FY16.** Series production of 8 cavity-coupler systems and 2 spares.
- **FY17.** Surface treatment and quality checks for 8 cavity-coupler systems and 2 spares.
- **FY18.** Completion of 8 cavity-coupler systems and 2 spares. Preparation of 8 cryostats, instrumentation and assembly equipment.
- **FY19.** Completion of 8 cryomodules and 2 spares with RF testing.

FY20. Delivery, acceptance test, installation and cryomodule commissioning.

The budget for cryomodule production from budget years FY16-FY20 will be updated with actual costs of materials and resources prior to the cryomodule construction review. This will also include the transportation, acceptance testing, and installation details for the LHC. As the project effort is in an embryonic stage, only coarse funding and resource allocation estimates are possible. A labour estimate of 2 FTEs within the US contribution is expected before project funding begins. A significant effort will be placed to improve the accuracy of the resources prior to the CD-0 status. This budget will include a contingency of 25% and scope of the overall budget as planned for the HL-LHC. Major budget items will be made compatible within the yearly US expenditure limits with a consistent contingency estimate.

Coarse cost estimates with the aim to achieve CD-0 status by FY13 and CD-2 status by FY16 are shown below. It should be noted that all expenditures before the project funds become available in the form of FTE's are made available by CERN, US-LARP, EuCARD and other collaborators.

Table 4: A coarse cost estimate (in M$) for a 10 year R&D and construction project aimed at fabrication of 8 compact crab cavity cryomodules with 2 spares ready for the use in the LHC for 2020/21 upgrade.

in M$	**FY11**	**FY12**	**FY13**	**FY14**	**FY15**	**FY16**	**FY17**	**FY18**	**FY19**	**FY20**
Phases	prototyping			pre-series			series production			
			CD-0			CD-2				
Cavities	0.85	0.57	0.37		0.4	1.35	1.35	1.35	1.35	
Couplers		0.57	0.57	0.65		1.4	1.9	1.9	1.9	0.6
He-Vessel/Tuner		0.15	0.15	0.3	0.1	0.45	0.45	0.45	0.45	
Cryostat				0.5	0.7	0.65	1.6	1.6	1.6	2.0
Instrumentation		0.1	0.1		0.3	0.3	0.3	0.2	0.2	0.1
Assembly/Testing			0.16	0.2	0.5			0.7	1.0	2.7
Annual Total	**0.85**	**1.29**	**1.35**	**1.65**	**2.0**	**4.15**	**5.6**	**6.2**	**6.5**	**5.4**

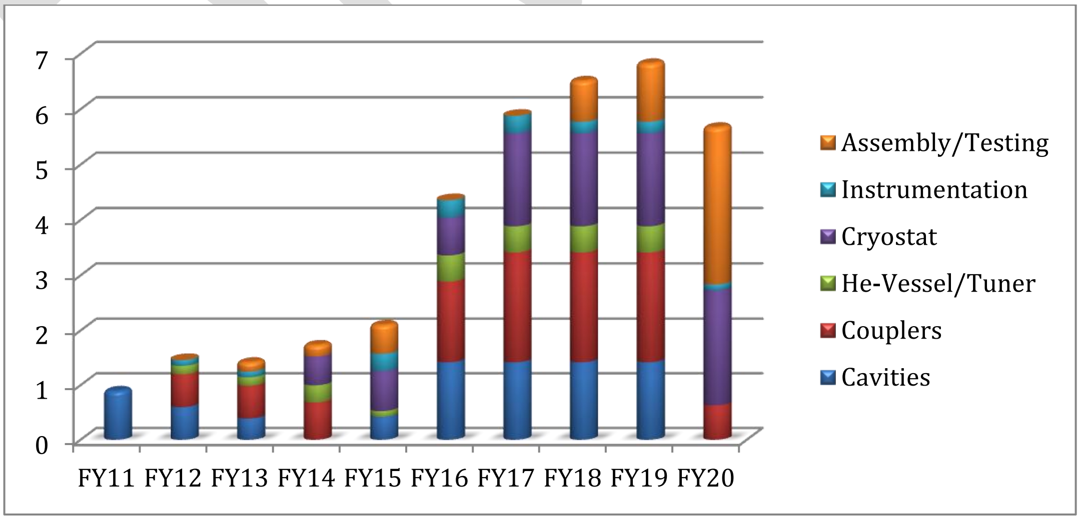


Figure 22: A budget profile estimate (in M$) for a 10 year R&D and construction project aimed at fabrication of 8 compact crab cavity cryomodules with 2 spares ready for the use in the LHC for 2020/21 upgrade.

9.3 ROLE OF US-LARP COLLABORATION

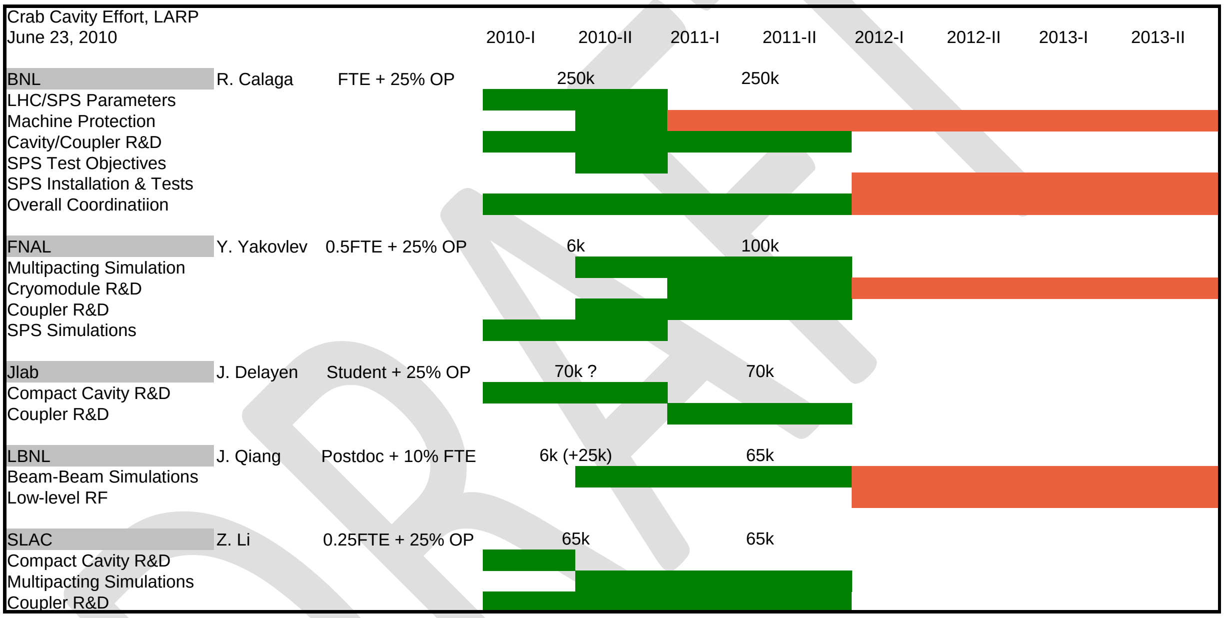
US LARP (BNL, FNAL, JLAB, LBL, SLAC)

Within the framework of the US-LARP program the studies on RF design on compact cavities, machine protection and other beam physics will continue through the FY2011. The primary technical contributions will aim at a final RF design of the single-rod and double-rod half-wave resonators as potential candidate for the compact cavities. Development of robust HOM damping schemes and tuning concepts for both cavities is anticipated to take place within the FY2011 funding cycle.

Contributions also from small business innovative proposals (SBIR/STTR) in close collaboration with the US-LARP institutions (for example: Niowave/JLAB) will complete a full RF, thermal and mechanical model of the double-rod half-wave resonator by the end of FY2011. This will initiate the cavity fabrication within the SBIR Phase II program.

A proposed US-LARP contribution up to the TDR phase is listed in Table 5.

Table 5: Proposed US-LARP contribution up to the TDR phase.



9.4 Role of European Partners & EuCARD

CEA, LAPP Annecy (IN2P3), LPSC

9.5 Role of KEK

KEK

10 Relevance to other R&D Work

(Synergies with other projects and studies, e.g. SCRF development, Deflecting cavities for accelerators, (JLAB) other ?

11 Conclusion

A viable strategy has been adopted. Follow both options (compact and conventional) in parallel in the study phase (at least). Because of the risk of major problems occurring with the compact cavity development the option of pursuing construction of the conventional cavity must be retained. It is also reasonable to assume that the conventional CC for the global scheme could be implemented and used some years earlier than a local scheme. Any lessons learned could be incorporated in the final system design. Etc. etc.

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